A METALLICITY-SPIN TEMPERATURE RELATION IN DAMPED LYMAN-α SYSTEMS

Nissim Kanekar[1], Alain Smette[2], Frank H. Briggs[3], Jayaram N. Chengalur[4]
Draft version September 14, 2009

ABSTRACT

We report evidence for an anti-correlation between spin temperature T_s and metallicity [Z/H], detected at 3.6σ significance in a sample of 26 damped Lyman-α absorbers (DLAs) at redshifts $0.09 < z < 3.45$. The anti-correlation is detected at 3σ significance in a sub-sample of 20 DLAs with measured covering factors, implying that it does not stem from low covering factors. We obtain $T_s = (-0.68 \pm 0.17) \times [\text{Z/H}] + (2.13 \pm 0.21)$ from a linear regression analysis. Our results indicate that the high T_s values found in DLAs do not arise from differences between the optical and radio sightlines, but are likely to reflect the underlying gas temperature distribution. The trend between T_s and [Z/H] can be explained by the larger number of radiation pathways for gas cooling in galaxies with high metal abundances, resulting in a high cold gas fraction, and hence, a low spin temperature. Conversely, low-metallicity galaxies have fewer cooling routes, yielding a larger warm gas fraction and a high T_s. Most DLAs at $z > 1.7$ have low metallicities, [Z/H] < -1, implying that the HI in high-z DLAs is predominantly warm. The anti-correlation between T_s and [Z/H] is consistent with the presence of a mass-metallicity relation in DLAs, suggested by the tight correlation between DLA metallicity and the kinematic widths of metal lines. Most high-z DLAs are likely to arise in galaxies with low masses ($M_{\text{vir}} < 10^{10.5} M_\odot$), low metallicities ([Z/H]< -1, and low cold gas fractions.

Subject headings: galaxies: evolution — galaxies: ISM — radio lines: galaxies

1. INTRODUCTION

Damped Lyman-α systems, with HI column densities $N_{\text{HI}} \geq 2 \times 10^{20}$ cm^{-2}, are the high-z gas-rich counterparts of today's normal galaxies, and crucial to understanding galaxy evolution. However, despite much observational effort, our knowledge of the typical size, structure and internal conditions of high z DLAs is yet limited (e.g. Wolfe et al. 2005). A controversial issue is the HI temperature distribution in the absorbers, whether most of the HI is in a warm, low-density phase (the warm neutral medium, WNM, with kinetic temperature $T_k \sim 5000 - 8000$ K; Wolfire et al. 1995), or whether a significant fraction is in a high density, cold phase (the CNM, with $T_k \sim 40 - 200$ K). For DLAs towards radio-loud quasars, this can be determined by combining the optical depth in the redshifted HI 21cm line with the HI column density measured from the Lyman-α profile to obtain the column-density-weighted harmonic mean spin temperature T_s along the sightline (e.g. Kanekar & Briggs 2004). High-z DLAs have been shown to have higher T_s values ($\gtrsim 700$ K; e.g. Wolfe & Davis 1979; Carilli et al. 1996; Kanekar & Chengalur 2003) than those typically found in the Milky Way or local spirals ($T_s \lesssim 300$ K; Braun & Walterbos 1992). The simplest interpretation of this, in the context of stable two-phase models, is that high-z DLAs contain larger WNM fractions than local disks (Carilli et al. 1996; Chengalur & Kanekar 2000). Conversely, Wolfe et al. (2003) argue that the detection of CII* absorption in a number of high-z DLAs indicates sizeable CNM fractions ($\sim 50\%$) in half the DLA population.

A plausible cause for the putative higher WNM fractions in high-z DLAs is their typically-low metallicity [Z/H], implying fewer routes for gas cooling. If high T_s values in DLAs arise due to low absorber metallicities, one would expect an anti-correlation between T_s and [Z/H], with low-T_s DLAs having high metallicities, and vice-versa (Kanekar & Chengalur 2001). We report here the detection of the predicted anti-correlation between T_s and [Z/H], supporting the conclusion that HI in high-z DLAs is predominantly in the warm neutral medium.

2. THE SAMPLE

Over the last decade, we have carried out HI 21cm absorption studies of DLAs towards compact, radio-loud quasars to measure their spin temperatures (e.g. Kanekar & Chengalur 2003; Kanekar et al. 2006, 2007; York et al. 2007), and have also measured the DLA covering factors through low-frequency very long baseline interferometry (VLBI) studies (Kanekar et al. 2009a). The VLBI images yield the fraction of compact radio emission, and thus a lower limit to the DLA covering factor. However, no additional radio emission is detected up to scales of $\sim 1''$, indicating that the remaining emission arises from much larger scales ($\gtrsim 10$ kpc), and is unlikely to be covered by the foreground DLA. The radio core fraction thus provides a good estimate of the DLA covering factor.

We have also obtained metallicity estimates for most of the DLAs with HI 21cm studies from our own observations or the literature. There are 26 DLAs, at $0.09 \lesssim z \lesssim 3.45$, with estimates of both T_s and [Z/H], of which 20 have covering factor estimates from low-frequency VLBI studies, and 21 have estimates of dust depletion, [Z/Fe]. The 26 absorbers of the sample are listed in Table 1, whose columns contain (1) the quasar name, (2) the DLA redshift, (3) the HI column density measured from the Lyman-α profile, (4) the DLA covering factor f, (5) the spin temperature T_s, or, for HI 21cm non-detections, the 3σ lower limit to T_s (taking into account the DLA covering factor, when known), (6) the metallicity [Z/H], (7) the dust depletion factor [Z/Fe], (8) the transitions used for the [Z/H] and [Z/Fe] estimates, and (9) references for [Z/H] and

[1] National Radio Astronomy Observatory, 1003 Lopezville Road, Socorro, NM87801, USA; nkanekar@nrao.edu
[2] European Southern Observatory, Alonso de Cordova 3107, Casilla 19001, Vitacura, Santiago, Chile
[3] RSAA, The Australian National University, Mount Stromlo Observatory, ACT 2611, Australia
[4] National Centre for Radio Astrophysics, TIFR, Ganeshkhind, Pune-411007, India

TABLE 1
THE FULL SAMPLE OF 26 DLAS.

QSO	z_{abs}	N_{HI} $\times 10^{20}$ cm^{-2}	f	T_s K	[Z/H]	[Z/Fe]	Z,Fe	Ref.
0738+313	0.0912	15 ± 2	0.98	775 ± 100	< -1.14	< 0.48	Zn,Fe	1
0738+313	0.2212	7.9 ± 1.4	0.98	870 ± 160	< -0.7	< 0.74	Zn,Cr	1
0952+179	0.2378	21.0 ± 2.5	0.66	6470 ± 965	< -1.02	< 0.63	Zn,Cr	1
1127−145	0.3127	51 ± 9	0.9	820 ± 145	-0.90 ± 0.11	−	Zn,−	2
1229−021	0.3950	5.6 ± 0.9	0.42	95 ± 15	-0.45 ± 0.14	> 0.83	Zn,Fe	3
0235+164	0.5242	50 ± 10	1.0	210 ± 45	-0.14 ± 0.17	1.73 ± 0.24	X-ray,Fe	4
0827+243	0.5247	2.0 ± 0.2	0.7	330 ± 65	-0.62 ± 0.05	−	Fe+0.4,−	1
1122−168	0.6819	2.8 ± 1	−	> 1445	< -1.47	< -0.15	Zn,Fe	1,2
1331+305	0.6922	17.8 ± 0.8	0.9	965 ± 105	-1.35 ± 0.03	0.28 ± 0.03	Zn,Fe	5
0454+039	0.8596	4.9 ± 0.2	0.5	> 690	-0.99 ± 0.12	0.00 ± 0.14	Zn,Fe	1
2149+212	0.9115	5 ± 1	−	> 2700	< -0.93	−	Zn,−	6
1331+170	1.7764	15 ± 1.4	0.72	1260 ± 335	-1.20 ± 0.04	0.847 ± 0.008	Zn,Fe	7
1157+014	1.9436	63 ± 15	0.63	1015 ± 255	-1.40 ± 0.10	0.38 ± 0.16	Zn,Fe	8
0458−020	2.0395	60 ± 10	1.0	560 ± 95	-1.27 ± 0.07	0.47 ± 0.05	Zn,Fe	7
0311+430	2.2898	2.0 ± 0.5	−	140 ± 35	> -0.6	−	Si,Fe	9
0432−440	2.3021	6.0 ± 1.4	−	> 995	-1.12 ± 0.15	0.33 ± 0.21	Si,Fe	10
0438−436	2.3474	6.0 ± 1.4	0.59	900 ± 250	-0.68 ± 0.15	0.62 ± 0.21	Zn,Fe	10
0405−331	2.5693	4.0 ± 0.9	0.44	> 785	-1.40 ± 0.15	0.34 ± 0.21	Si,Fe	10
0913+003	2.7434	5.5 ± 1.3	−	> 800	-1.47 ± 0.15	0.12 ± 0.21	Si,Fe	10
1354−170	2.7799	2.0 ± 0.7	−	> 795	-1.86 ± 0.16	0.67 ± 0.10	Si,Fe	7
2342+342	2.9084	13 ± 3	0.71	> 1705	-1.23 ± 0.15	0.36 ± 0.13	Zn,Fe	11
0537−286	2.9742	2.0 ± 0.5	0.47	> 520	< -0.44	−	Zn,Fe	10
0336−017	3.0619	15.8 ± 3.6	0.68	> 6670	-1.40 ± 0.10	0.37 ± 0.03	S,Fe	7
0335−122	3.1799	6.0 ± 1.4	0.62	> 1850	-2.56 ± 0.15	0.05 ± 0.21	Si,Fe	10
0201+113	3.3875	18 ± 3	0.76	1050 ± 175	-1.26 ± 0.15	0.18 ± 0.21	S,Fe	12
1418−064	3.4482	2.5 ± 0.6	0.69	> 680	-1.48 ± 0.15	0.24 ± 0.21	Si,Fe	10

Notes: The T_s values have been re-computed uniformly by Kanekar et al. (*in prep.*). References for [Z/H] values are mostly to literature compilations, which contain the original references; all values are scaled to the solar abundances of Lodders (2003). (1) Kulkarni et al. (2005); (2) Kanekar et al. (*in prep.*); (3) Boisse et al. (1998); (4) Junkkarinen et al. (2004); (5) Wolfe et al. (2008); (6) Nestor et al. (2008); (7) Prochaska et al. (2007); (8) Ledoux et al. (2006); (9) Ellison et al. (2008); (10) Akerman et al. (2005); (11) Prochaska et al. (2003b); (12) Ellison et al. (2001).

[Zn/Fe] values. In all but two cases, $Z \equiv Zn, S, Si$, in order of preference. The exceptions are the $z \sim 0.524$ DLAs towards 0235+164 and 0827+243, where the metallicities are, respectively, from an X-ray spectrum (Junkkarinen et al. 2004) and [Z/H]=[Fe/H]+0.4 [following Prochaska et al. (2003a)]. The sample contains 14 T_s measurements and 12 lower limits, and 20 [Z/H] measurements, five upper limits, and one lower limit (towards 0311+430; Ellison et al. 2008). Detailed references for the metallicities and spin temperatures are provided in Kanekar et al. (*in prep.*).

Note that the sample does not include four systems where the radio emission is clearly extended on scales $>> 1''$, and the covering factor is likely to be low, $f << 1$; these are the H I 21cm absorbers at $z \sim 0.437$ towards 3C196 (Briggs et al. 2001) and $z \sim 0.656$ towards 3C336 (Curran et al. 2007a) (where the H I 21cm absorption arises towards extended lobes, with little radio flux density associated with the quasar core), and the H I 21cm non-detections at $z \sim 1.3911$ towards QSO 0957+561 and $z \sim 1.4205$ towards PKS 1354+258 (Kanekar & Chengalur 2003). We have also excluded "associated" DLAs, lying within ~ 3000 km s^{-1} of the quasar, as conditions in these absorbers could be affected by their proximity to an active galactic nucleus.

Preliminary results of this study showing the anti-correlation between T_s and [Z/H] were presented in Kanekar & Chengalur (2005). Curran et al. (2007b) later also found weak evidence for the anti-correlation, but did not have covering factor estimates for most high-z DLAs, and hence could not rule out the effects of unknown covering factors. The results of the present *Letter* are based on new H I 21cm data on 11 absorbers, and VLBI estimates of the DLA covering factor for most systems, and yield the first clear evidence for a relation between the metallicity and the H I temperature distribution in the absorbers.

3. RESULTS: AN ANTI-CORRELATION BETWEEN T_s AND [Z/H]

Fig. 1[A] shows T_s plotted versus [Z/H] for the 26 DLAs of the full sample; it is apparent that low T_s values ($\lesssim 300$ K) are obtained at high metallicities ([Z/H]$\gtrsim -0.6$), while high T_s values $\gtrsim 700$ K are found at low metallicities, [Z/H]$\lesssim -1$. We used the non-parametric generalized Kendall rank correlation statistic (Brown et al. 1974; Isobe et al. 1986), as implemented in the ASURV package (the BHK statistic), to test for a correlation between T_s and [Z/H], treating the latter as the independent variable. This allows limits in both variables to be treated consistently. Errors on individual measurements were handled through a Monte-Carlo approach, using the measured values and 1σ errors for each absorber to generate 10^4 sets of 26 pairs of [Z/H] and T_s values. The statistical significance of the BHK statistic quoted below is the average of values obtained in these 10^4 trials. For the full sample, the anti-correlation is detected at $\sim 3.6\sigma$ significance; the probability of this arising by chance is $\sim 3 \times 10^{-4}$. If we exclude the $z = 0.524$ DLA towards 0235+164 (whose metallicity is from an X-ray study), and use [Fe/H] as a lower limit to [Z/H] for the DLA towards 0827+243, the anti-correlation is detected
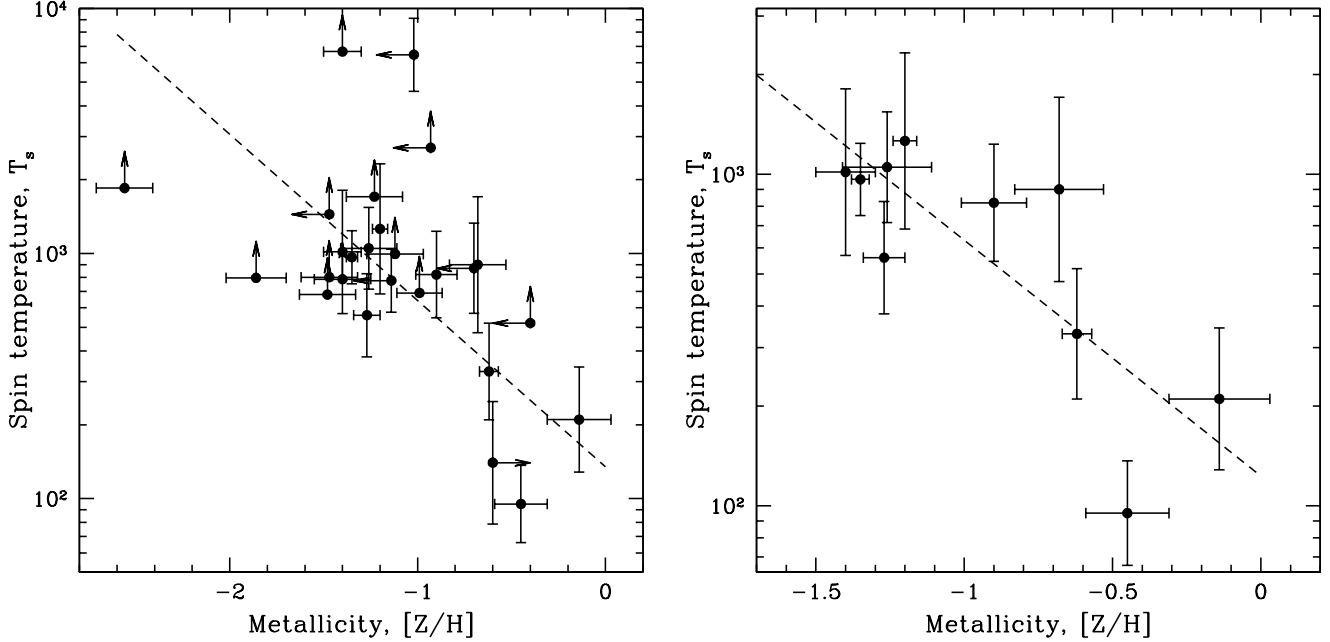
FIG. 1.— The spin temperature T_s plotted against metallicity, [Z/H], for [A] (left panel) the 26 DLAs of the full sample, and [B] (right panel) the ten DLAs with measurements of both T_s and [Z/H]. The dashed line shows the linear fit to the relation between [Z/H] and T_s.

at $\sim 3.1\sigma$ significance, showing that it does not arise from incorrect metallicity estimates in these absorbers.

A linear regression analysis was used to obtain the best-fit relation between T_s and [Z/H], using the ten systems with measurements of both T_s and [Z/H] (i.e. excluding all limits), all of which also have covering factor estimates; these are shown in Fig. 1[B]. The BCES(Y/X) estimator (Akritas & Bershady 1996) was used for this purpose, treating [Z/H] as the independent variable X; this method takes into account measurement errors on both variables, as well as the possibility that these errors are correlated (which applies here, as T_s and [Z/H] are both derived from N_{HI}). We obtain $T_s = (-0.68 \pm 0.17) \times [Z/H] + (2.13 \pm 0.21)$; the fit is shown as a dashed line in Figs. 1[A] and [B]. Excluding the DLAs towards 0235+164 and 0827+243 yields $T_s = (-0.77 \pm 0.40) \times [Z/H] + (2.02 \pm 0.48)$, from eight DLAs with measurements of T_s and [Z/H].

We also tested for a correlation between the dust depletion factor [Z/Fe] and T_s, using the 21 systems with estimates of both quantities. The anti-correlation between [Z/Fe] and T_s has $\sim 2.2\sigma$ significance, reducing to $\sim 1.6\sigma$ significance on excluding the possibly-unreliable X-ray metallicity estimate in the DLA towards 0235+164. We thus do not find significant evidence for a relation between [Z/Fe] and T_s, although this sub-sample contains few DLAs with low spin temperatures.

Curran et al. (2007b) note that an observed anti-correlation between T_s and metallicity might arise due to unknown low covering factors. We hence estimated the BHK statistic for the sub-sample of 20 DLAs with covering factor estimates (Kanekar et al. 2009a). The anti-correlation between T_s and [Z/H] is then detected at $\sim 3\sigma$ significance, with a probability of ~ 0.003 of chance occurrence. Low covering factors are thus unlikely to be the cause of the anti-correlation between T_s and [Z/H].

It is possible that the observed anti-correlation between T_s and [Z/H] is not a "primary" relation, but stems from an underlying relation between other physical quantities (e.g. ve-

locity spread and metallicity; Ledoux et al. 2006). For example, Curran et al. (2007b) argue that an observed correlation between T_s and [Z/H] might arise due to a relation between the velocity spread of HI 21cm absorption ΔV_{21} and the rest equivalent width of the MgIIλ2796 line, $W_0^{\lambda 2796}$, each tracing the dynamics of the absorber. They note that $T_s \propto N_{HI}/\left[\int \tau_{21}dV\right] \approx N_{HI}/\left[\tau_{21,\max}\Delta V_{21}\right]$, suggesting that $T_s \propto 1/\Delta V_{21}$. $W_0^{\lambda 2796}$ is known to correlate with metallicity (Murphy et al. 2007), so, if ΔV_{21} also correlates with $W_0^{\lambda 2796}$, the three relations could yield an observed anti-correlation between T_s and [Z/H]. However, the HI column density in DLAs does not correlate with either [Z/H] or $W_0^{\lambda 2796}$ (e.g. Rao et al. 2006), and the DLAs of Table 1 have N_{HI} values extending over ≈ 1.5 dex. If the T_s–[Z/H] relation arises due to an underlying relation between ΔV_{21} and $W_0^{\lambda 2796}$, this spread in N_{HI} values would imply that the T_s–[Z/H] relation would be *weaker* than the relation between ΔV_{21} and $W_0^{\lambda 2796}$ (and vice-versa, if the T_s–[Z/H] relation is the "primary" relation). In other words, the "primary" relation would have the highest statistical significance in samples of similar size, as uncorrelated (and variable) parameters like N_{HI} would dilute the significance of any derived relations.

Kanekar et al. (2009b) used the BHK test to test for correlations between $W_0^{\lambda 2796}$ and both the HI 21cm velocity spread ΔV_{21} and the integrated HI 21cm optical depth $\int \tau_{21}dV$, in a sample of MgII absorbers and DLAs. They found the putative correlation between ΔV_{21} and $W_0^{\lambda 2796}$ to have $\sim 1.7\sigma$ significance (with 23 absorbers), and that between $\int \tau_{21}dV$ and $W_0^{\lambda 2796}$ to have $\sim 2.2\sigma$ significance (with 24 absorbers). Both these trends are significantly weaker than the relation between T_s and [Z/H] found here ($\sim 3.6\sigma$ significance), in samples of similar size. It is thus unlikely that the anti-correlation between T_s and [Z/H] arises from an underlying relation between $W_0^{\lambda 2796}$ and either ΔV_{21} or $\int \tau_{21}dV$. The present data indicate that the anti-correlation between T_s and [Z/H] is the

"primary" relation, given its higher statistical significance.

4. DISCUSSION

High spin temperature estimates in high-z DLAs have been the focus of much debate, with suggestions that these might arise due to different sightlines at optical and radio wavelengths (Wolfe et al. 2003) or low covering factors (Curran et al. 2005). It is possible that individual T_s measurements might be in error due to these effects. However, recent low-frequency VLBI studies have shown that high T_s values are not the result of low DLA covering factors (Kanekar et al. 2009a). Further, the anti-correlation between T_s and [Z/H] is detected in the sub-sample of DLAs with covering factor measurements, indicating that this relation too is not caused by low covering factors. Finally, differing optical and radio sightlines (e.g. if the radio emission is extended on scales larger than the size of the optical quasar) would result in T_s estimates that are uncorrelated with the "true" T_s values along the optical sightline. This would *weaken* any underlying correlation between T_s and a quantity like [Z/H], measured along the pencil beam towards the optical quasar. The detection of the predicted anti-correlation between T_s and [Z/H] thus indicates that line-of-sight issues are also not the source of the observed high T_s values. We conclude that the high T_s estimates in high-z DLAs are most likely to arise due to larger WNM fractions in DLAs than typical in local spiral galaxies.

In the local universe, the metallicity and mass of galaxies are known to be correlated (e.g. Tremonti et al. 2004). A similar correlation, between metallicity and stellar mass, has been found in emission-selected, high-z galaxies (e.g. Savaglio et al. 2005). Evidence for a mass-metallicity relation in DLAs is unclear. Ledoux et al. (2006) argue that the observed correlation between the kinematic width of unsaturated low-ionization metal profiles ΔV_{90} and metallicity in high-z DLAs arises from an underlying mass-metallicity relation. Conversely, Zwaan et al. (2008) note that ΔV_{90} is a weak indicator of galaxy mass at $z = 0$, as the kinematic width measured along a pencil beam depends on the galaxy inclination and the impact parameter. However, the above correlation between ΔV_{90} and metallicity has been reproduced in simulations (Pontzen et al. 2008), which suggest that it does stem from a mass-metallicity relation. Pontzen et al. (2008) find that sightlines through DLAs with low virial masses, $M_{\rm vir} < 10^{9.5} M_\odot$, typically yield low metallicities, [Z/H]$\lesssim -1.7$, while the typical metallicities are [Z/H]~ -1.2 in intermediate-mass galaxies ($M_{\rm vir} \sim 10^{9.5-10.5} M_\odot$), and [Z/H]$\gtrsim -1$ in high-mass systems ($M_{\rm vir} > 10^{10.5} M_\odot$; for comparison, $M_{\rm vir} \sim 10^{12} M_\odot$ for the Milky Way; e.g. Xue et al. 2008). Interestingly, Prochaska et al. (2008) find a tight correlation between the rest equivalent width in the saturated Si IIλ1526 line W_{1526} and metallicity, and argue that W_{1526} tracks dynamical motions in the halos of DLAs, with the correlation between W_{1526} and [Z/H] arising due to a mass-metallicity relation of the same slope as that seen in low-z galaxies.

If a mass-metallicity relation is present in DLAs, low-mass DLAs would have low metallicities. Low-mass galaxies also have low thermal pressures, while a high pressure is needed for the formation of a stable multi-phase medium at a low metallicity. Fig. 6 of Wolfire et al. (1995) shows that, at low pressures and metallicities, H I exists mostly in the warm phase. Sightlines through such galaxies would thus typically yield a high spin temperature. Con-

versely, the mass-metallicity relation implies that high-mass DLAs would have high metallicities, along with high thermal pressures. Such galaxies would have significant CNM fractions, with most sightlines yielding low spin temperatures. These effects would yield the anti-correlation between T_s and [Z/H] detected here, due to the paucity of cooling routes in low-metallicity galaxies (Norman & Spaans 1997; Kanekar & Chengalur 2001; Kanekar & Briggs 2004). The anti-correlation between T_s and [Z/H] is thus consistent with the presence of a mass-metallicity relation in DLAs (Ledoux et al. 2006; Prochaska et al. 2008); low-metallicity DLAs are likely to have high T_s values due to their low CNM fractions.

While the relation between T_s and [Z/H] is consistent with the presence of a mass-metallicity relation in DLAs, it is also possible that the T_s–[Z/H] relation is a local one, arising due to line-of-sight issues. For disk galaxies, the cross-section for DLA incidence is largest for sightlines through the outskirts of the galaxy. If high-z DLAs have steep metallicity gradients, such sightlines would typically encounter low metallicities (e.g. Zwaan et al. 2005). The lack of *local* cooling routes could then result in low CNM fractions, and high T_s values along these sightlines. Conversely, sightlines through the central regions of large disk galaxies would typically have high metallicities and high CNM fractions. Such line-of-sight effects could thus also yield the anti-correlation of Fig. 1. While such steep metallicity gradients have not been seen in local galaxies and low-z DLAs (typical gradients are $\sim -0.03 - -0.04$ dex kpc^{-1}; Chen et al. 2005; Bresolin et al. 2009), they are not ruled out in high-z DLAs. We note, in passing, that the $z \sim 0.524$ DLA towards 0827+243 has one of the largest DLA impact parameters (~ 27 kpc; Steidel et al. 2002), and yet has both a low T_s (330 K) and a high metallicity, [Z/H]$= -0.6$.

Fig. 1[A] shows that low T_s values are only found in DLAs with [Z/H]$\gtrsim -0.6$. Only 13 of the 153 DLAs at $z > 1.6$ in the sample of Prochaska et al. (2007) have such high metallicities; the majority of high-z DLAs have [Z/H]< -1.0. The anti-correlation between T_s and [Z/H] then implies that most high z DLAs have high T_s values. Conversely, six of seventeen DLAs at $z \lesssim 1$ have [Z/H]≥ -0.6 (e.g. Prochaska et al. 2003a; Kulkarni et al. 2005). While the number of metallicity measurements at $z < 1$ is yet small, the present data indicate a higher fraction of high-metallicity DLAs at low redshifts. If so, the T_s–[Z/H] anti-correlation implies that the fraction of DLAs with high CNM fraction should also be larger at $z \lesssim 1$. This is consistent with the observed increase in the detection rate of H I 21cm absorption in DLAs at $z \lesssim 1$ (Kanekar et al. 2009b).

Finally, Wolfe et al. (2003) found that the strong CII* lines detected in half their DLAs could not be explained by absorption in pure WNM, and implied the presence of cold H I. They argue that H I in DLAs without CII* absorption is likely to be predominantly warm, but that a two-phase model with a CNM fraction of $\sim 50\%$ is consistent with the observed bolometric luminosity in systems with CII* detections. However, lower CNM fractions are not ruled out. For example, the $z \sim 3.39$ DLA towards PKS 0201+113 shows strong CII* absorption (Wolfe et al. 2003), but has a low metallicity, [S/H]$= -1.26$ (Ellison et al. 2001), and a low CNM fraction, $\lesssim 17\%$ (Kanekar et al. 2007). This suggests that, while DLAs showing CII* absorption contain *some* CNM, the H I content of low-metallicity absorbers is still likely to be dominated by

the WNM (see also Srianand et al. 2005).

5. SUMMARY

We report the detection of an anti-correlation between spin temperature and metallicity (with $\sim 3.6\sigma$ significance in the non-parametric BHK test) in a sample of 26 DLAs at $0.09 < z < 3.45$. For 20 systems, the absorber covering factor has been estimated from low-frequency VLBI studies; the anti-correlation between T_s and [Z/H] is detected here at $\sim 3\sigma$ significance. A linear regression analysis using the BCES estimator finds the relation $T_s = (-0.68 \pm 0.17) \times [Z/H] + (2.13 \pm 0.21)$ between T_s and [Z/H]. Low spin temperatures, $T_s \lesssim 300$ K, are only found in high-metallicity DLAs (with [Z/H]$\gtrsim -0.6$), while high T_s values ($\gtrsim 700$ K) are obtained in low-metallicity ([Z/H]< -1) absorbers. The fact that a relation is seen between T_s and [Z/H] implies that the high T_s values in DLAs are unlikely to be an artifact arising from differences between radio and optical sightlines through the absorbers, and are instead likely to reflect the underlying gas temperature distribution. The majority of DLAs at $z > 1.6$ have [Z/H]< -1, implying that most of the HI in DLAs must be in the warm phase, with small CNM fractions. The observed anti-correlation between T_s and [Z/H] is consistent with independent evidence for the presence of a mass-metallicity relation in DLAs. The majority of high-z DLAs are likely to be galaxies of low mass and metallicity, with most of the neutral gas in the warm phase.

REFERENCES

Akerman, C. J., Ellison, S. L., Pettini, M., & Steidel, C. C. 2005, A&A, 440, 499

Akritas, M. G. & Bershady, M. A. 1996, ApJ, 470, 706

Boisse, P., Le Brun, V., Bergeron, J., & Deharveng, J.-M. 1998, A&A, 333, 841

Braun, R. & Walterbos, R. 1992, ApJ, 386, 120

Bresolin, F., Ryan-Weber, E., Kennicutt, R. C., & Goddard, Q. 2009, ApJ, 695, 580

Briggs, F. H., de Bruyn, A. G., & Vermeulen, R. C. 2001, A&A, 373, 113

Brown, B. W. M., Hollander, M., & Korwar, R. M. 1974, in Reliability and Biometry, ed. F. Proschan & R. J. Serfling (Philadelphia: SIAM), 327

Carilli, C. L., Lane, W. M., de Bruyn, A. G., Braun, R., & Miley, G. K. 1996, AJ, 111, 1830

Chen, H.-W., Kennicutt, Jr., R. C., & Rauch, M. 2005, ApJ, 620, 703

Chengalur, J. N. & Kanekar, N. 2000, MNRAS, 318, 303

Curran, S. J., Murphy, M. T., Pihlström, Y. M., Webb, J. K., & Purcell, C. R. 2005, MNRAS, 356, 1509

Curran, S. J., Tzanavaris, P., Murphy, M. T., Webb, J. K., & Pihlstroem, Y. M. 2007a, MNRAS, 381, L6

Curran, S. J., Tzanavaris, P., Pihlström, Y. M., & Webb, J. K. 2007b, MNRAS, 382, 1331

Ellison, S. L., Pettini, M., Steidel, C. C., & Shapley, A. E. 2001, ApJ, 549, 770

Ellison, S. L., York, B. A., Pettini, M., & Kanekar, N. 2008, MNRAS, 388, 1349

Isobe, T., Feigelson, E. D., & Nelson, P. I. 1986, ApJ, 306, 490

Junkkarinen, V. T., Cohen, R. D., Beaver, E. A., Burbidge, E. M., Lyons, R. W., & Madejski, G. 2004, ApJ, 614, 658

Kanekar, N. & Briggs, F. H. 2004, New Astr. Rev., 48, 1259

Kanekar, N. & Chengalur, J. N. 2001, A&A, 369, 42

—. 2003, A&A, 399, 857

Kanekar, N. & Chengalur, J. N. 2005, in IAU Colloq. 199: Probing Galaxies through Quasar Absorption Lines, ed. P. Williams, C.-G. Shu, & B. Menard (Cambridge University Press, Cambridge), 156

Kanekar, N., Chengalur, J. N., & Lane, W. M. 2007, MNRAS, 375, 1528

Kanekar, N., Lane, W. M., Momjian, E., Briggs, F. H., & Chengalur, J. N. 2009a, MNRAS, 394, L61

Kanekar, N., Prochaska, J. X., Ellison, S. L., & Chengalur, J. N. 2009b, MNRAS, 396, 385

Kanekar, N., Subrahmanyan, R., Ellison, S. L., Lane, W. M., & Chengalur, J. N. 2006, MNRAS, 370, L46

Kulkarni, V. P., Fall, S. M., Lauroesch, J. T., York, D. G., Welty, D. E., Khare, P., & Truran, J. W. 2005, ApJ, 618, 68

Ledoux, C., Petitjean, P., Fynbo, J. P. U., Møller, P., & Srianand, R. 2006, A&A, 457, 71

Lodders, K. 2003, ApJ, 591, 1220

Murphy, M. T., Curran, S. J., Webb, J. K., Ménager, H., & Zych, B. J. 2007, MNRAS, 376, 673

Nestor, D., Pettini, M., Hewett, P., Rao, S., & Wild, V. 2008, MNRAS (accepted; arxiv/0808.2470)

Norman, C. A. & Spaans, M. 1997, ApJ, 480, 145

Pontzen, A., Governato, F., Pettini, M., Booth, C. M., Stinson, G., Wadsley, J., Brooks, A., Quinn, T., & Haehnelt, M. 2008, MNRAS, 390, 1349

Prochaska, J. X., Chen, H.-W., Wolfe, A. M., Dessauges-Zavadsky, M., & Bloom, J. S. 2008, ApJ, 672, 59

Prochaska, J. X., Gawiser, E., Wolfe, A. M., Castro, S., & Djorgovski, S. G. 2003a, ApJ, 595, L9

Prochaska, J. X., Gawiser, E., Wolfe, A. M., Cooke, J., & Gelino, D. 2003b, ApJS, 147, 227

Prochaska, J. X., Wolfe, A. M., Howk, J. C., Gawiser, E., Burles, S. M., & Cooke, J. 2007, ApJS, 171, 29

Rao, S. M., Turnshek, D. A., & Nestor, D. B. 2006, ApJ, 636, 610

Savaglio, S. et al. 2005, ApJ, 635, 260

Srianand, R., Petitjean, P., Ledoux, C., Ferland, G., & Shaw, G. 2005, MNRAS, 362, 549

Steidel, C. C., Kollmeier, J. A., Shapley, A. E., Churchill, C. W., Dickinson, M., & Pettini, M. 2002, ApJ, 570, 526

Tremonti, C. A. et al. 2004, ApJ, 613, 898

Wolfe, A. M. & Davis, M. M. 1979, AJ, 84, 699

Wolfe, A. M., Gawiser, E., & Prochaska, J. X. 2003, ApJ, 593, 235

—. 2005, ARA&A, 43, 861

Wolfe, A. M., Jorgenson, R. A., Robishaw, T., Heiles, C., & Prochaska, J. X. 2008, Nature, 455, 638

Wolfire, M. G., Hollenbach, D., McKee, C. F., Tielens, A. G. G. M., & Bakes, E. L. O. 1995, ApJ, 443, 152

Xue, X. X. et al. 2008, ApJ, 684, 1143

York, B. A., Kanekar, N., Ellison, S. L., & Pettini, M. 2007, MNRAS, 382, L53

Zwaan, M., Walter, F., Ryan-Weber, E., Brinks, E., de Blok, W. J. G., & Kennicutt, R. C. 2008, AJ, 136, 2886

Zwaan, M. A., van der Hulst, J. M., Briggs, F. H., Verheijen, M. A. W., & Ryan-Weber, E. V. 2005, MNRAS, 364, 1467